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ENDOCRINE DISRUPTORS AND HORMONAL DYSREGULATION IN AQUATIC VERTEBRATES: MECHANISMS AND ECOTOXICOLOGICAL CONSEQUENCES

Narrative Review (ID: 1676)

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ABSTRACT

Background: Endocrine-disrupting chemicals (EDCs) are emerging aquatic pollutants that interfere with normal hormonal regulation in vertebrates. These contaminants enter aquatic ecosystems mainly through industrial discharge, agricultural runoff, pharmaceutical residues, municipal wastewater effluents, and urban pollution.
Objective: This review aims to summarize the major sources, mechanisms, and ecotoxicological consequences of EDC exposure in aquatic vertebrates, particularly fish and amphibians.
Methods: This narrative review synthesizes current literature on endocrine disruption in aquatic vertebrates, with emphasis on contaminant classes, hormonal pathways, biological effects, biomarkers, adverse outcome pathways, and emerging molecular and computational tools used for endocrine toxicity assessment.
Discussion: Evidence indicates that EDC exposure can cause reproductive dysfunction, feminization, intersex conditions, thyroid disruption, developmental abnormalities, altered behaviour, and reduced population sustainability. Amphibians are especially vulnerable because their metamorphosis is strongly dependent on thyroid hormone regulation. Key mechanisms include hormone receptor interference, altered steroidogenesis, oxidative stress, mitochondrial dysfunction, epigenetic modifications, and disruption of gene expression. Recent advances in molecular tools, adverse outcome pathway frameworks, zebrafish models, and artificial intelligence-based prediction systems have improved the detection and assessment of endocrine toxicity.
Conclusion: EDCs pose a significant threat to aquatic vertebrates by disrupting reproductive, developmental, thyroid, behavioural, and ecological processes. Their long-term effects may contribute to biodiversity loss, population decline, and ecosystem instability. Improved environmental monitoring, wastewater treatment, regulatory control, and advanced toxicity assessment tools are essential to reduce the ecological risks associated with endocrine-disrupting pollutants.

Keywords: Endocrine-disrupting chemicals; aquatic vertebrates; hormonal dysregulation; ecotoxicological effects; endocrine toxicity mechanisms; fish; amphibians.

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INTRODUCTION

Endocrine disrupting chemicals (EDCss) are one of the most important groups of environmental pollutants that pose a serious risk to aquatic ecosystems globally (García-Fernández et al., 2021). Exposure to these compounds disrupts the normal production, release, movement, breakdown, receptor binding, and removal of endogenous hormones, thus altering normal endocrine function in exposed organisms (Guarnotta et al., 2022). All aquatic organisms, especially fish, amphibians and reptiles, are at risk, as aquatic ecosystems serve as "last stop" for industrial, agricultural, pharmaceutical, and household pollutants (Ogidi et al., 2022). Aquatic organisms are chronically exposed to complex mixtures of endocrine active substances (EAS) in freshwater and marine environments due to continuous discharge of wastewater, pesticides, plasticizers, personal care products, pharmaceuticals, heavy metals and synthetic hormones (Maqbool et al., 2023).

Endocrine system is responsible for controlling other physiological functions like growth, reproduction, metabolism, development, osmoregulation, stress responses, and immune function by maintaining tightly controlled hormonal signalling pathways (Ahsan et al., 2020). In aquatic vertebrates, these pathways can lead to serious developmental and reproductive defects, compromising the stability of the population and the integrity of the ecosystem (Bănăduc et al, 2022). EDCs can pose as a natural hormone, inhibit hormone receptors, disrupt the production of hormones, or disrupt the neuroendocrine signalling cascade. Therefore, these chemicals can cause feminisation, masculinisation, intersexed features, impaired gonadal development, reduced fertility, behavioural changes, thyroid disorders and transgenerational effects (Amir et al., 2021). Recent evidence shows that endocrine disruption extends beyond reproductive hormones to include thyroid, adrenal, corticosteroid and metabolic endocrine axes (Egalini et al.,2022).

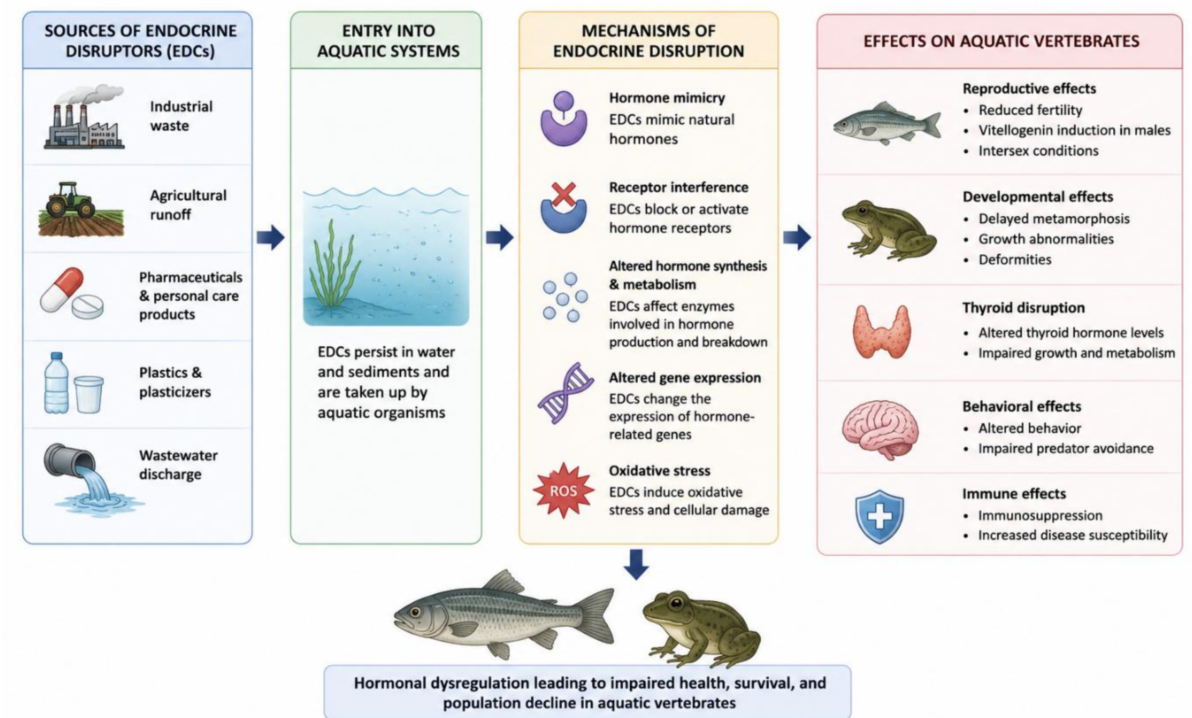

Figure 1. Mechanisms of endocrine disruption and hormonal dysregulation in aquatic vertebrates.

There are several anthropogenic sources of EDCs to aquatic ecosystems. Increased concentrations of pharmaceutical and hormonal compounds are not removed at all from municipal wastewater treatment plants, and these are considered as major contributors (Pironti et al., 2021). Pesticides, herbicides, veterinary hormones and fertilizer associated contaminants are added to rivers and lakes by agricultural runoff. Bisphenols, phthalates, polychlorinated biphenyls (PCBs), dioxins, heavy metals, and per and polyfluoroalkyl substances (PFAS) are among the contaminants that are released by industrial effluents, and microplastics and personal care products (PCPs) by urban stormwater (Rashmi et al., 2020). Endocrine activities in aquatic systems are further enhanced by the natural hormones excreted by humans and livestock. Many EDCs are persistent, bioaccumulate, and are biologically active at levels of nanograms or picograms (Pironti et al., 2021).

Fish are among aquatic vertebrates that are known to be sensitive bioindicators of endocrine disruption due to the fact that they have direct and lifelong exposure with contaminated water (Dietrich et al., 2022). A large number of studies in both field and laboratory

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settings have reported fish population reproductive and developmental abnormalities in response to EDC exposure (Celino Brady et al., 2021). Vitellogenin induction, vitellogenic effect on testicles, decreased sperm qualities, feminization of secondary sexual characteristics are common features observed in male fish exposed to estrogenic compounds like 17α ethinylestradiol, bisphenol A (BPA), and nonylphenol (Alavi et al., 2021). Androgenic contaminants, on the other hand, can lead to masculinization and changes in reproductive behavior in females. Thyroid Disrupter Chemicals have adverse effects on neural development, metabolic regulation and growth. Chronic exposure may deplete the fitness of species and their biodiversity by decreasing fecundity, larval survival, predator avoidance behaviour, and immune competence (Morthorst et al., 2023).

Indeed, amphibians are one of the most vulnerable groups of vertebrates for endocrine disruption, because of their permeable skin, their biphasic life cycle and their dependence on hormones for metamorphosis (Dang et al.,2022). Thyroid hormones are very important in amphibian development and thus these species are extremely sensitive to thyroid disrupting pollutants. Frogs and salamanders have been linked to feminisation, gonadal abnormalities, delayed metamorphosis and disrupted sex differentiation due to herbicides, including atrazine (Babalola et al., 2021). In the case of amphibians, hermaphroditism and biased sex ratios have been reported in contaminated wetlands by several studies. Global declines in amphibian biodiversity have been attributed, at least in part, to chronic exposure to EACs, habitat loss, and climate change (Lambert et al.,2021).

Table 1. Major Classes of Endocrine Disrupting Chemicals (EDCs) and Their Effects in Aquatic Vertebrates

Class of EDCs	Common Examples	Major Sources	Mechanism of Action	Effects on Aquatic Vertebrates
Bisphenols	BPA, BPS	Plastics, bottles, packaging materials	Estrogen receptor mimicry	Feminization, reproductive abnormalities
Phthalates	DEHP, DBP	Plasticizers, cosmetics	Hormone synthesis interference	Reduced fertility, endocrine imbalance
Pesticides	Atrazine, DDT	Agricultural runoff	Aromatase alteration, receptor disruption	Delayed metamorphosis, sex reversal
Pharmaceuticals	Ethinylestradiol, antidepressants	Wastewater effluents	Hormonal pathway disruption	Behavioural and reproductive changes
Heavy metals	Lead, cadmium, mercury	Industrial discharge	Oxidative stress and endocrine toxicity	Thyroid dysfunction, developmental defects
PFAS	PFOA, PFOS	Industrial products, firefighting foams	Endocrine receptor interference	Metabolic and reproductive disturbances
PCBs & Dioxins	Polychlorinated biphenyls	Industrial pollutants	Thyroid and steroid hormone disruption	Neurodevelopmental and immune effects
Microplastics	Plastic particles	Marine and freshwater pollution	Carrier of hydrophobic EDCs	Bioaccumulation and hormonal dysregulation

The mechanisms of EDCs are complex, involving several molecular pathways. Many compounds interact directly with nuclear hormone receptors such as estrogen receptors (ERs), androgen receptors (ARs), thyroid hormone receptors (TRs), glucocorticoid receptors, and peroxisome proliferator activated receptors (PPARs) (Toporova et al., 2020). The other types of modulators affect the expression or activity of enzymes such as aromatase, cytochrome P450 enzymes, and hydroxysteroid dehydrogenase (Rajakumar et al., 2020). Recently, epigenetic modifications, oxidative stress, mitochondrial dysfunction, and altered gene transcription are regarded as important pathways in endocrine mediated toxicity (Cano et al., 2021). Furthermore, the presence of mixtures of contaminants can cause additive, synergistic, or antagonistic interactions, which makes the toxicological assessment and ecological risk prediction more complicated (Cheng et al., 2024). In the past, molecular ecotoxicology has enhanced the knowledge of endocrine disruption in aquatic vertebrates. Transcriptomics, proteomics, metabolomics, and adverse outcome pathway (AOP) frameworks are rapidly being used to characterize the toxicological response from exposure and to predict ecological effects of exposure (Li et al., 2025). The zebrafish (Danio rerio) is a prominent model organism because of its genetic resemblance to higher vertebrates, transparent embryos and sensitivity to endocrine active pollutants (F Ghanem et al., 2021). Zebrafish models have shown that EDCs can disrupt immune function, neurodevelopment, reproductive signaling and embryogenesis by complex molecular mechanisms. Also, new computational tools, such as quantitative structure–activity relationship (QSAR) models, and artificial intelligence (AI) screening systems are being developed to predict the endocrine activity of novel contaminants (Takesono et al., 2022).

Potential ecological impacts of endocrine disruption are not only on individual organisms, but may also impact community structure and ecosystem functioning. Population declines and biodiversity losses can result from reduced reproductive success, changed predator prey dynamics, migration impairments, behavioural changes and developmental abnormalities (Samuel et al., 2023). Aquatic vertebrates fill key trophozoological niche positions and are capable of transmitting endocrine disrupting effects through the food web, thus affecting ecological balance. Chronic exposures can also cause transgenerational and evolutionary effects, which can change the adaptive capacity of exposed populations. This can have serious implications for environmental sustainability, fisheries productivity, and the conservation of aquatic biodiversity (Parker et al., 2023). Emerging contaminants like microplastics, nanoplastics, pharmaceutical residues, and new industrial chemicals are becoming a focus of recent interest. Microplastics have intrinsic endocrine disrupting properties and can also carry hydrophobic contaminants such as persistent organic pollutants (POPs), heavy metals, phthalates and bisphenols (Bossio et al., 2025). Large distribution in aquatic habitats increases bioavailability and toxicity of chemicals for vertebrates. Additionally, stressors to the climate system, including temperature, hypoxia, and salinity changes, can interact with EDC exposure, exacerbating endocrine disruption and ecotoxicological effects. These multiple stresses are an important topic of current environmental research (Lee et al., 2026).

Although significant advances have been made in understanding endocrine disrupting mechanisms, there are still significant gaps in environmental monitoring, mixture toxicity assessment and regulatory management. Traditional toxicological strategies are not well suited to the issues of low dose chronic exposure, non monotonic dose response, and/or multigenerational effects found with EDCs (Holmer et al., 2025). Contaminant levels in the environment are also often spatially and temporally variable, which makes risk assessment challenging. Integrated frameworks integrating molecular biomarkers, ecological endpoints, and population level evaluations are thus increasingly being called for to enhance environmental protection strategies by international agencies and regulatory authorities (Cui et al., 2026). Thus, it is necessary to understand the mechanisms that cause endocrine disruption in aquatic vertebrates in order to predict ecological consequences and to develop effective mitigation measures (Kloas et al., 2024). The study and understanding of the molecular, physiological, reproductive, developmental, and ecological effects of EDC exposure will help in the betterment of environmental risk assessment and sustainable management of aquatic ecosystems (Ghosh et al., 2022). The purpose of this review is to provide a thorough overview of the major groups of endocrine disruptors that impact aquatic vertebrate organisms, how they cause disruption to the endocrine system, and the resulting ecotoxicological consequences, at the organismal, population, and ecosystem levels. The objective of this review is to provide a comprehensive narrative synthesis of the major classes, sources, mechanisms, and ecotoxicological consequences of endocrine disrupting chemicals in aquatic vertebrates. This review specifically aims to describe how endocrine disruptors interfere with hormonal signalling pathways in fish, amphibians, and other aquatic vertebrates; summarize their reproductive, developmental, thyroid-related, behavioural, and population-level effects; and highlight the role of biomarkers, adverse outcome pathways, molecular tools, and computational approaches in improving endocrine toxicity assessment and environmental risk prediction.

REVIEW METHODOLOGY

This review was designed as a narrative review with thematic synthesis to summarize the available evidence on endocrine disruptors and hormonal dysregulation in aquatic vertebrates. A comprehensive literature search was conducted to identify relevant studies, reviews, and reports related to endocrine disrupting chemicals, their sources, mechanisms of action, biological effects, and ecotoxicological consequences in fish, amphibians, and other aquatic vertebrate species. The literature search was performed using major scientific databases and search platforms, including PubMed, Google Scholar, ScienceDirect, Scopus, Web of Science, SpringerLink, and relevant journal databases. The search mainly focused on literature published between 2020 and 2026, while older articles were considered where they provided important background information, mechanistic explanation, or foundational toxicological concepts. The search terms used alone and in combination included: “endocrine disrupting chemicals,” “endocrine disruptors,” “aquatic vertebrates,” “fish endocrine disruption,” “amphibian endocrine disruption,” “hormonal dysregulation,” “thyroid disruption,” “reproductive toxicity,” “bisphenol A,” “phthalates,” “PFAS,” “pesticides,” “microplastics,” “zebrafish model,” “adverse outcome pathway,” “ecotoxicology,” “biomarkers,” “QSAR,” and “artificial intelligence in toxicology.”

Studies were considered eligible if they discussed endocrine disrupting chemicals in aquatic ecosystems, mechanisms of hormonal interference, reproductive or developmental toxicity in aquatic vertebrates, thyroid-related effects, molecular biomarkers, mixture toxicity, adverse outcome pathways, or ecological consequences at organismal, population, or ecosystem levels. Review articles, experimental studies, mechanistic studies, toxicological assessments, and environmental monitoring studies were included where they were relevant to the scope of the review. Studies focusing only on human endocrine disorders without aquatic or ecotoxicological relevance, articles with insufficient methodological or scientific detail, duplicate publications, and non-relevant reports were excluded. The selected literature was reviewed and organized into major thematic domains, including sources and classes of endocrine disruptors, mechanisms of hormonal dysregulation, reproductive toxicity in fish, thyroid-mediated developmental disruption, amphibian sensitivity, biomarkers of endocrine disruption, mixture toxicity, emerging molecular and computational tools, and ecological or regulatory implications. The findings were synthesized narratively rather than statistically because of the heterogeneity of study designs, species, exposure conditions, contaminants, endpoints, and outcome measures. Therefore, no meta-analysis was performed.

The purpose of this methodological approach was to provide a broad and integrated understanding of endocrine disruption in aquatic vertebrates by linking contaminant exposure with molecular mechanisms, physiological effects, reproductive and developmental outcomes, and wider ecotoxicological consequences.

LITERATURE REVIEW

The presence of EDCs in aquatic ecosystems has emerged as a significant threat to aquatic ecotoxicology due to their capacity to disrupt hormonal signaling pathways in vertebrates (Jasrotiaet al., 2021). More recent research has shown that aquatic life is constantly exposed to a variety of endocrine active contaminants, such as pharmaceuticals, pesticides, plasticizers, industrial chemicals and steroid hormones (Sefali et al., 2026). These pollutants cause reproductive, developmental, metabolic and behavioural abnormalities in fish and amphibians, impacting aquatic biodiversity and ecosystem sustainability (Mallicket al., 2025). Research on the mechanism of action of endocrine disrupting chemicals (EDCs), molecular markers, thyroid related effects, adverse outcome pathways, and ecological effects in aquatic vertebrates is particularly current (Karyakina et al., 2026). Collard et al. (2024) studied thyroid mediated endocrine disruption in aquatic vertebrates and suggested an approach for selecting endocrine disrupting substances in non mammalian species. The authors noted the importance of thyroid disruption in the growth, neurodevelopment, and metabolism of fish and amphibians, as well as in metamorphosis. They found that mechanistic evidence, adverse effects and population level outcomes play key roles in the process of ecological risk assessment. The study also suggested internationally standardised guidelines for the regulatory evaluation of endocrine disruptors in aquatic environments.

Peskova et al (2025) reviewed the effects of Bisphenols on fish endocrinology and found that BPs, including BPS and BPA, have a significant effect on the reproductive physiology, gonadal development, and endocrine balance in fish. They found that bisphenol exposure causes feminization, production of vitellogenin by males, oxidative stress, and reduced reproductive success. The authors also mentioned that chronic exposure may negatively impact fish population dynamics and ecosystem health through the impairment of reproduction by endocrine mediated mechanisms. Malafaia et al. (2025) examined the concept of zooplankton based adverse outcome pathways (AOPs) for the evaluation of endocrine disrupting compounds (EDCs) in aquatic ecosystems. The study was able to determine the molecular initiating events and key biological responses of endocrine disruption in aquatic organisms. They highlighted the importance of AOP frameworks for their ability to offer mechanistic understanding of endocrine toxicity and to enhance environmental monitoring programmes. The authors concluded that integrating omics technologies and ecotoxicological biomarkers can enhance prediction of long term ecological consequences.

Pinto et al. (2026) presented a comprehensive overview of endocrine disruptors in aquatic vertebrates and highlighted the increasing occurrence of endocrine active pollutants in freshwater ecosystems. The study proved that pesticides, plasticizers, and industrial chemicals are disrupting the reproduction of fish and amphibians and the processes of development. The authors presented evidence of gonadal abnormalities, changes in steroidogenesis and reproductive fitness in exposed vertebrates. Additionally, the study stressed the importance of zebrafish as an effective model organism for endocrine disruption studies. Yazdan et al. (2022) investigated the occurrence and sources of hormones in aquatic systems and their environmental implications. They showed that both natural and synthetic hormones in wastewater effluents accumulate in aquatic environments and have endocrine disrupting effects at very low levels. The research suggested that steroid hormones have a marked effect on the reproductive physiology, developmental regulation and hormonal balance of aquatic vertebrates. The authors highlighted that better wastewater treatment technology and stricter environmental regulations are needed to reduce the contamination of hormones.

Heidari et al. (2023) investigated endocrine disruption in teleost fishes and amphibians of anthropogenic and environmental stressors. They pointed out that endocrine disruptions are heavily affected by pesticides, climate change stresses and industrial pollutants. The authors noted that amphibians are especially sensitive since thyroid hormones control metamorphosis and development. Amphibians became feminized, had delayed metamorphosis, abnormal sex differentiation and reproductive abnormalities when exposed to contaminants like atrazine. The study also highlighted the potential for synergy between environmental stressors and EDs to amplify environmental risks. Socha et al. (2024) reviewed the effects and toxicity of endocrine disrupting chemicals in fish. The authors reported changes in gonadosomatic index, gamete quality, reproductive behaviour and endocrine signaling pathways in aquatic species exposed to EDC. The scientists found that estrogenic chemicals cause intersex and reproductive dysfunction, and androgenic chemicals alter their secondary sex characteristics and their mating behaviour. The review found that exposure to EDs over long periods of time poses a risk to the stability of fish populations and aquatic biodiversity.

In vivo, in vitro and in silico techniques for experimental characterization of endocrine disrupting effects in fish were discussed by Jiskoot et al. (2025) The study showed that these new and innovative molecular methods, such as transcriptomics, metabolomics, and receptor binding assays, can greatly enhance the detection of endocrine active compounds. Zebrafish models were found to be very useful in the study of developmental toxicity, neuroendocrine disruption, and reproductive abnormalities. The authors proposed that a combination of the above experimental strategies would improve the understanding of endocrine disrupting mechanisms and ecological effects. Evangelista et al. (2025) created a deep learning quantitative structure–activity relationship (QSAR) model to predict estrogen receptor binding endocrine disruptors. They found that AI driven screening methods are crucial in detecting hazardous endocrine active substances. The model successfully predicted compounds that could interact with the estrogen receptors and affect the endocrine signaling. The authors suggest that computational tools for toxicology could be used to aid in conducting ecological risk assessment more quickly and to reduce the need for extensive animal testing in endocrine disruption studies.

Baker (2022) explored the evolutionary divergence of the receptor proteins for progesterone and mineralocorticoids in fish and terrestrial vertebrates and implications for endocrine disruption. The study found that the endocrine disrupting chemicals interact differently with the steroid receptors among the vertebrate species due to the functional divergence and evolution of the receptors. The author showed that certain chemicals like bisphenol A and pesticides can bind to steroid hormone receptors and interfere with reproductive and developmental processes in fish. The study highlighted the need to take into account species specific endocrine responses in environmental risk assessment of endocrine disruptors.

Table 2: Selected Studies on Endocrine Disruptors and Hormonal Dysregulation in Aquatic Vertebrates

Sr. No.	Title of Study	Year	Thematic Outcome Analysis	Reference
1	Endocrine disruption assessment in aquatic vertebrates – Identification of substance induced thyroid mediated effect patterns	2024	Proposed thyroid disruption assessment framework for aquatic vertebrates and highlighted ecological consequences of thyroid dysfunction	Collard et al.,2024)
2	Bisphenols: Endocrine Disruptors and Their Impact on Fish: A Review	2025	Reported reproductive toxicity, feminization, and oxidative stress caused by bisphenols in fish	Peskova & Blahova, 2025
3	Zooplankton based adverse outcome pathways: A tool for assessing endocrine disrupting compounds in aquatic environments	2024	Identified molecular pathways and biomarkers for endocrine toxicity assessment	Razak et al., 2024
4	Endocrine Disruptors in Aquatic Vertebrates	2021	Highlighted reproductive and developmental endocrine disruption in fish and amphibians	Moreira et al., 2021
5	Occurrence and sources of hormones in water resources environmental and health impact	2024	Demonstrated accumulation of hormonal contaminants in aquatic systems and their endocrine effects	Grzegorzek et al., 2024
6	Endocrine disruption in teleosts and amphibians is mediated by anthropogenic and natural environmental factors	2024	Reported feminization, delayed metamorphosis, and altered sex differentiation in amphibians	Kloas et al., 2024
7	Endocrine disrupting chemicals and their harmful effects in fish: A comprehensive review	2024	Showed reproductive impairment, intersex conditions, and endocrine dysfunction in fish	Ramasre et al., 2024
8	Experimental Approaches for Characterizing the Endocrine Disrupting Effects of Environmental Chemicals in Fish	2021	Discussed advanced molecular and experimental approaches for endocrine toxicity evaluation	Fabbri et al., 2021
9	Predicting Endocrine Disruptors: A Deep Learning QSAR Model for Estrogen Receptor Activity	2026	Developed AI based prediction models for estrogenic endocrine disruptors	Desai et al., 2026
10	Divergent Evolution of Progesterone and Mineralocorticoid Receptors in Terrestrial Vertebrates and Fish Influences Endocrine Disruption	2021	Explained species specific receptor responses to endocrine disrupting chemicals	Baker, 2021

DISCUSSION

Widespread Occurrence of Endocrine Disruptors in Aquatic Ecosystems

The widespread occurrence of endocrine-disrupting chemicals (EDCs) in aquatic ecosystems represents a growing ecotoxicological concern because these compounds are persistent, biologically active at very low concentrations, and capable of bioaccumulating within aquatic food chains (Onyime et al., 2026). The reviewed literature indicates that freshwater and marine habitats are continuously exposed to endocrine-active contaminants through multiple anthropogenic pathways, including agricultural runoff, pharmaceutical disposal, industrial discharge, municipal wastewater effluents, and urban pollution (Akindurodoye et al., 2026). This continuous input creates conditions for long-term, low-dose exposure among aquatic vertebrates, particularly fish and amphibians. The evidence synthesized in this review shows that hormones, pesticides, bisphenols, plasticizers, pharmaceuticals, and industrial chemicals are among the most frequently reported contaminants interfering with endocrine signalling in aquatic vertebrates (Ullah et al., 2023). Their persistence in water and sediments increases the probability of chronic exposure, even when individual contaminants are present at apparently low concentrations. This is particularly important because EDCs may produce biological effects at environmentally relevant doses and may not always follow conventional dose–response patterns. Therefore, the presence of EDCs in aquatic ecosystems should not be viewed only as a contamination issue, but also as a long-term biological threat to reproductive success, developmental stability, and ecosystem sustainability. These findings highlight the need for improved monitoring systems, targeted pollution-control strategies, and stronger regulation of chemical discharge into aquatic environments (Medkova et al., 2023).

Mechanisms of Hormonal Dysregulation

The studies reviewed suggest that EDCs produce hormonal dysregulation through multiple interconnected molecular and physiological pathways rather than through a single mechanism. Many EDCs can mimic, block, or alter the action of naturally occurring hormones by

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interacting with estrogen, androgen, thyroid, progesterone, and corticosteroid receptors (Zou et al., 2020). This receptor-level interference can disturb normal endocrine communication and lead to abnormal reproductive, developmental, metabolic, and behavioural outcomes in aquatic vertebrates. In addition to receptor binding, several EDCs affect steroidogenesis by altering enzymes involved in steroid hormone synthesis, metabolism, and transport. Disruption of these pathways can modify circulating hormone levels and disturb endocrine feedback mechanisms. More recent mechanistic evidence also suggests that oxidative stress, mitochondrial dysfunction, epigenetic changes, and abnormal gene expression contribute significantly to endocrine-mediated toxicity (Rajakumar et al., 2020). These mechanisms are particularly important because they may explain delayed, cumulative, and even transgenerational effects observed after EDC exposure. Overall, the evidence indicates that endocrine disruption is a complex biological process involving cross-talk between reproductive, thyroid, metabolic, stress-related, and developmental endocrine axes. Therefore, the assessment of EDC toxicity requires an integrated approach that considers both direct hormonal interference and broader cellular or molecular changes (Yilmaz et al., 2020).

Reproductive Toxicity in Fish

Reproductive toxicity is one of the most consistently reported consequences of endocrine disruption in fish. The reviewed studies show that exposure to estrogenic contaminants, including bisphenols and synthetic hormones, can induce feminization, vitellogenin production in male fish, gonadal abnormalities, and intersex conditions (F Ghanem et al., 2021). These findings indicate that EDCs can interfere with normal sexual differentiation and reproductive physiology, particularly in species with continuous exposure to contaminated aquatic environments. Chronic exposure to EDCs may also impair gamete quality, reproductive behaviour, fertility, and spawning success. These effects are not limited to individual organisms; they may gradually reduce reproductive efficiency at the population level. When fewer viable offspring are produced or when reproductive behaviour is altered, long-term population stability may be compromised. The reviewed evidence also suggests that endocrine toxicity can occur at environmentally relevant concentrations, making low-dose exposure a major concern in aquatic ecotoxicology (Alavi et al., 2021). Therefore, reproductive endpoints such as gonadal development, vitellogenin induction, gamete quality, sex ratio, and spawning success should be considered central indicators in the environmental assessment of EDC exposure in fish.

Thyroid Hormone Disruption and Developmental Effects

Thyroid-mediated endocrine disruption is another important mechanism through which EDCs affect aquatic vertebrates, particularly developing fish and amphibians (Deal et al., 2020). Thyroid hormones play a central role in growth, metabolism, neurodevelopment, and metamorphosis. Any disruption in thyroid hormone synthesis, transport, metabolism, receptor binding, or signalling can therefore result in serious developmental consequences. The reviewed studies indicate that thyroid-disrupting chemicals (TDCs) may cause delayed metamorphosis, altered growth patterns, abnormal larval development, and neurological dysfunction (Mourouzis et al., 2020). These effects are especially relevant in amphibians because their life cycle depends heavily on precise thyroid hormone regulation during metamorphosis. Even minor disturbance in thyroid signalling may delay or impair the transition from larval to adult stages, thereby reducing survival and reproductive capacity. In fish, thyroid disruption may also affect growth, metabolic regulation, and neurodevelopment. Collectively, these findings suggest that thyroid disruption may contribute to developmental instability and population-level decline in sensitive aquatic species. This makes thyroid-related endpoints an important component of ecological risk assessment for EDCs (Zwahlen et al., 2024).

Amphibian Sensitivity to Endocrine Disruption

Amphibians appear to be particularly vulnerable to EDC exposure because of their permeable skin, aquatic and terrestrial life stages, and strong dependence on hormonal regulation during development and metamorphosis. The reviewed studies reported feminization, hermaphroditism, altered sex differentiation, gonadal abnormalities, and reproductive impairment in amphibian species exposed to pesticides and industrial pollutants (Kloas et al., 2024). These findings suggest that amphibians may act as sensitive bioindicators of endocrine contamination in aquatic and semi-aquatic environments. Atrazine exposure has been particularly associated with gonadal abnormalities and altered sex ratios, although the severity of effects may depend on species, exposure duration, dose, and environmental conditions. The vulnerability of amphibians may be further increased by additional stressors such as temperature changes, habitat destruction, hypoxia, and climate-related ecological disturbances. Therefore, endocrine disruption should be interpreted as part of a wider ecological stress framework rather than as an isolated toxicological event. The interaction between EDC exposure and environmental stressors may contribute to reduced survival, impaired reproduction, and global amphibian biodiversity loss (Guimarães Ervilha et al., 2025).

Ecotoxicological Consequences at Population and Ecosystem Levels

The ecological consequences of EDC exposure extend beyond individual-level abnormalities and may affect entire aquatic populations and ecosystems. Reduced reproductive success, developmental abnormalities, altered behaviour, impaired predator avoidance, and increased vulnerability to environmental stress may collectively reduce survival and population stability (Isibor et al., 2026). These effects are particularly concerning because small physiological or reproductive changes at the organismal level can accumulate over time and produce measurable ecological consequences. Changes in fish and amphibian populations may also disturb trophic interactions and food-web dynamics. For example, a decline in reproductively competent individuals may reduce population recruitment, while altered behaviour may change predator–prey relationships. Long-term exposure may also produce transgenerational effects, potentially affecting the adaptive capacity of exposed populations. The reviewed studies therefore suggest that endocrine disruption should not be regarded only as a toxicological issue, but also as a conservation and ecosystem-management challenge. The combined effects of reduced fertility, developmental impairment, behavioural disruption, and population decline may ultimately threaten aquatic biodiversity and ecosystem balance (Deknock et al., 2020).

Role of Emerging Technologies in Endocrine Disruption Research

Recent advances in molecular biology, ecotoxicology, and computational toxicology have improved the understanding of endocrine disruption in aquatic vertebrates. The reviewed literature highlights the increasing use of transcriptomics, metabolomics, receptor-binding assays, and adverse outcome pathways (AOPs) for identifying biomarkers and mechanistic pathways of endocrine toxicity (Wiklund et al., 2025). These approaches allow researchers to connect molecular initiating events with cellular, physiological, organismal, and population-level outcomes. The zebrafish model has been particularly valuable because of its genetic similarity to higher vertebrates, transparent embryos, rapid development, and sensitivity to endocrine-active compounds. Zebrafish-based studies provide important insights into developmental toxicity, reproductive disruption, neuroendocrine effects, and gene-expression changes. In addition, artificial intelligence and deep learning-based quantitative structure–activity relationship (QSAR) models are emerging as useful tools for predicting the endocrine-disrupting potential of new or poorly studied chemicals (F Ghanem et al., 2021). These technologies may improve early hazard identification, reduce reliance on extensive animal testing, and support more efficient ecological risk assessment. However, their usefulness depends on the quality of input data, validation across species, and integration with real-world ecological endpoints.

Table 3. Biomarkers Used for Detection of Endocrine Disruption in Aquatic Vertebrates

Biomarker	**Biological Significance**	**Organism Commonly Used**	**Indicator of**
Vitellogenin induction	Marker of estrogenic exposure	Fish	Feminization and estrogenic activity
Gonadosomatic Index (GSI)	Assessment of reproductive organ development	Fish and amphibians	Reproductive toxicity
Thyroid hormone levels (T3/T4)	Evaluation of thyroid function	Amphibians and fish	Thyroid disruption
Aromatase activity	Regulation of steroidogenesis	Fish	Altered sex differentiation
Oxidative stress enzymes	Assessment of cellular stress response	Fish	Reactive oxygen species-mediated toxicity
Histopathological changes	Evaluation of tissue-level damage	Fish gonads/liver	Chronic endocrine exposure
Gene expression analysis	Molecular assessment of endocrine response	Zebrafish	Hormonal pathway alteration
Behavioural alterations	Assessment of neuroendocrine effects	Fish and amphibians	Neurological disruption
Hatching and larval survival	Marker of developmental toxicity	Fish embryos	Embryotoxicity
Sex ratio changes	Population-level endocrine marker	Fish and amphibians	Feminization or masculinization

Mixture Toxicity and Environmental Complexity

A major issue identified in the reviewed literature is that aquatic organisms are rarely exposed to a single contaminant. Instead, they are usually exposed to complex mixtures of EDCs and other pollutants that may produce additive, synergistic, or antagonistic effects. This creates a major challenge for toxicological evaluation because the biological effect of a chemical mixture may be more severe or less predictable than the effect of each compound alone (Goutam Mukherjee et al., 2022). Mixture toxicity is especially important in aquatic ecosystems where wastewater effluents, agricultural chemicals, plastic-derived compounds, pharmaceuticals, heavy metals, and industrial contaminants may occur together. These combined exposures can interfere with multiple endocrine axes at the same time, increasing the complexity of biological responses. Environmental conditions such as temperature, salinity, pH, oxygen availability, and climate-related stressors may further modify the toxicity of EDCs. Therefore, laboratory studies based on single-chemical exposure may not fully reflect real ecological conditions. Future ecotoxicological research should give greater attention to environmentally realistic exposure scenarios, mixture-based risk assessment, and the interaction between EDCs and changing environmental conditions (Canosa et al., 2023).

Regulatory Challenges and Future Perspectives

Despite significant scientific progress, the regulation of EDCs remains challenging because these compounds may act at very low concentrations, produce non-monotonic dose responses, and cause chronic or delayed effects that are difficult to detect through traditional toxicity testing (Toso et al., 2023). Species-specific sensitivity further complicates risk assessment, as fish, amphibians, and other aquatic vertebrates may respond differently to the same contaminant. Conventional toxicological methods may therefore underestimate the ecological risks associated with endocrine-active chemicals (Mitchell et al., 2023). The reviewed evidence supports the need for a more integrated regulatory framework that combines molecular biomarkers, reproductive and developmental endpoints, ecological indicators, and population-level assessments. Improved wastewater treatment technologies, stricter control of industrial and agricultural discharge, and safer chemical-management policies are necessary to reduce the entry of EDCs into aquatic environments. Future research should also focus on long-term ecological monitoring, transgenerational effects, mixture toxicity, climate-related interactions, and the validation of new approach methodologies. Overall, effective management of endocrine disruption requires a shift from single-chemical toxicity testing toward broader ecosystem-based risk assessment.

CONCLUSION:

Endocrine disruptors pose a major potential risk to aquatic vertebrates through disruption of hormonal regulation in the organism on multiple levels. The reviewed evidence indicates consistent effects on reproduction, development, thyroid function and behaviour in fish and amphibians. These disruptions result in lower fertility, changes in sex characteristics, developmental abnormalities, and decreases in the population. The amphibians are sensitive animals because they need thyroid hormones for metamorphosis. Overall, endocrine disruption is not only toxic to individuals, but also affects ecosystem structure and biodiversity. There are still problems with mixture toxicity, low dose reaction and long-term ecological effects. To minimize the ecological hazards that EDCs pose, the environmental regulations need to be strengthened, the wastewater treatment improved, and advanced molecular or computational tools used.

AUTHOR CONTRIBUTION

Author	Contribution
Aisha Siddiqa	Conceptualization, methodology, literature search, writing – original draft, validation, supervision, and final approval of the manuscript
Khadeejat ul Kubra Nangrejo	Methodology, investigation, data curation, literature review, and writing – review and editing
Kamran Khan	Investigation, data curation, thematic analysis, reference management, and writing – review and editing
Muhammad Shahbaz Azhar	Formal analysis, validation, figure/table preparation, and writing – original draft support
Muhammad Hashim	Critical review, writing – review and editing, intellectual input, and final manuscript revision

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